Dynamic Force Simulator for Force Feedback Human-Machine Interaction

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Abstract

In this paper we propose a Dynamic Force Simulator (DFS) for force feedback in human-machine systems. The DFS simulates object dynamics, contact model and friction characteristics of the human hand interacting with objects in a Virtual Reality environment. After derivation of kinematic and force relations between hand and object space we propose a method for calculation and feedback of appropriate forces to the force controlled actuators of the sensor glove we have developed.

1 Introduction

As a step to human friendly technical systems we have proposed the Intelligent Assisting System – IAS, which assists human operators performing mechanical manipulations in the task environment[2][3]. To influence the environment state physical actions must be exerted on objects, which we call flow of power. Of course flow of information is equally important, but only the combination comes close to what humans do everyday in their environment.

The idea of the IAS considers these information and power flows and aims at physical manipulation assistance as a first step. Information flow means various data from sensors, task goals, etc. and power flow consists of forces and work between operator, the IAS and the task environment. In the following information and power flow is abbreviated as IP-flow.

As a first approach to realization of the IAS we are developing a Skill Acquisition and Transfer System including a force feedback sensor glove device and virtual world graphics animation interface (see Fig.1). Central issue for realistic force feedback to the human operator is the Dynamic Force Simulator DFS proposed in this paper.

Research in artificial world and human-machine interfaces has so far concentrated on high-quality graphics animation and was less concerned about force feedback. The development of effective force feedback devices is just in the beginning phase, where some rather sophisticated devices have emerged[1][4][7]. We strongly think that an easy to use human-machine interface has to include some force exchange too. The sensor glove device we have developed has 10

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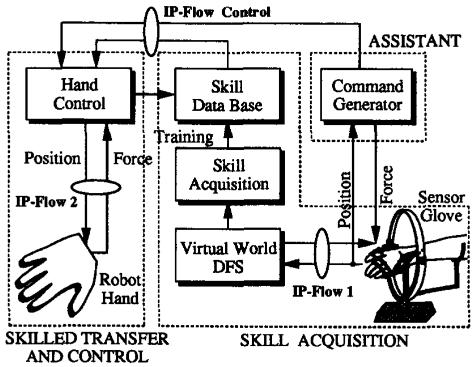


Figure 1: Structure of the Skill Acquisition and Transfer System.

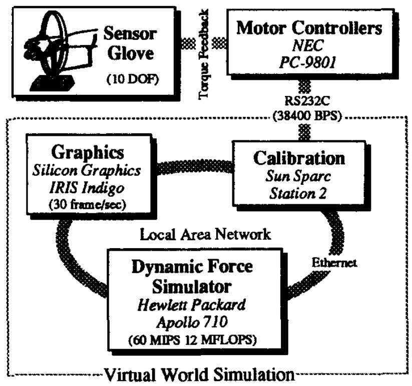


Figure 2: DFS Experimental System Structure.

degrees-of-freedom, 3 degrees of freedom for the wrist, 3 for the index finger, 2 for the thumb and 2 for the rest of the fingers. In this paper we propose a method for realization of the DFS with detailed derivation of the information and power flows during interaction of the human operator and objects in the virtual environment. The experimental system structure of the DFS is shown in Figure 2.

For real-time graphics animation a Silicon Graphics IRIS workstation is used displaying the state of the hand and object in the virtual world at a frame rate of 30 frames per second. A SPARC II workstation calibrates the sensor glove joint angles using an Artificial Neural Network approach. The overall network of these computing resources enables parallel processing of graphics, DFS calculations, motion control and sensor glove calibration in real-time.

2 Realization of DFS

While manipulating an object the generalized external force $\boldsymbol{f}_{ext} \in \mathcal{R}^6$ interacts with forces $\boldsymbol{f}_i$ from the fingers in contact with the object(Fig.4). The object is moved by the force $\boldsymbol{f}_o$ (gravity and the inertia force) and the force $\boldsymbol{f}_h$ exerted by the hand. After balancing $\boldsymbol{f}_o - \boldsymbol{f}_h$ the remainder is fed back to the human hand yielding force perception or acts on the object as an acceleration force.

2.1 Coordinate Transformations Between Hand and Object

Figure 4 illustrates the transformations between finger-tip, contact and object coordinate frames. Let us define transformation matrices $\boldsymbol{U}_i \in \mathcal{R}^{4\times4}$ and $\boldsymbol{V}_i \in \mathcal{R}^{4\times4}$, where $\boldsymbol{U}_i$ transforms from the finger-tip coordinate frame $\boldsymbol{T}_i \in \mathcal{R}^{4\times4}$ to the contact frame $\boldsymbol{C}_i \in \mathcal{R}^{4\times4}$, and $\boldsymbol{V}_i \in \mathcal{R}^{4\times4}$ from the contact frame to the object frame $\boldsymbol{B} \in \mathcal{R}^{4\times4}$ as

$$\boldsymbol{T}_i \xrightarrow{\boldsymbol{U}_i} \boldsymbol{C}_i \xrightarrow{\boldsymbol{V}_i} \boldsymbol{B} \; . \tag{1}$$

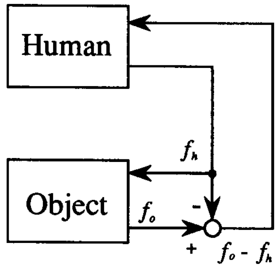


Figure 3: Relation between Human and Object

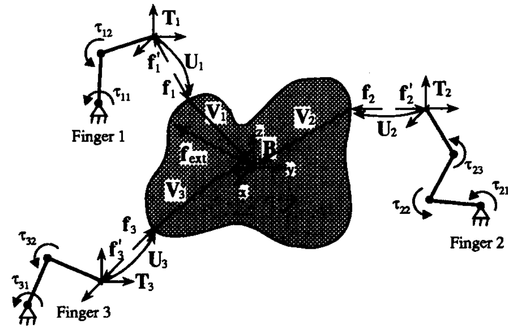


Figure 4: Object Grasped by 3 Fingers

The x- and y-axis of the contact coordinate frame $\boldsymbol{C}_i$ are tangents and the z-axis is perpendicular to the object surface curvature.

The transformation matrices $\boldsymbol{\Gamma}_i \in \mathcal{R}^{6\times 6}$ and $\boldsymbol{\Lambda}_i \in \mathcal{R}^{6\times 6}$ are defined such that $\boldsymbol{\Gamma}_i$ transforms finger-tip forces ${}^{T_i}\boldsymbol{f}_i$ into forces ${}^{C_i}\boldsymbol{f}_i$ in the contact coordinate frame and $\boldsymbol{\Lambda}_i$ transforms these to forces ${}^{B}\boldsymbol{f}_i$ in the object reference frame $\boldsymbol{B}$ as

$$ {}^{T_i}\boldsymbol{f}_i \xrightarrow{\boldsymbol{\Gamma}_i} {}^{C_i}\boldsymbol{f}_i \xrightarrow{\boldsymbol{\Lambda}_i} {}^{B}\boldsymbol{f}_i \,. \tag{2} $$

The relations of (1) and (2) can be written as

$$ \boldsymbol{C}_i = \boldsymbol{T}_i\,\boldsymbol{U}_i \quad , \quad \boldsymbol{B} = \boldsymbol{C}_i\,\boldsymbol{V}_i = \boldsymbol{T}_i\,\boldsymbol{U}_i\,\boldsymbol{V}_i \tag{3} $$

$$ {}^{C_i}\boldsymbol{f}_i = \boldsymbol{\Gamma}_i\,{}^{T_i}\boldsymbol{f}_i \quad , \quad {}^{B}\boldsymbol{f}_i = \boldsymbol{\Lambda}_i\,{}^{C_i}\boldsymbol{f}_i = \boldsymbol{\Lambda}_i\,\boldsymbol{\Gamma}_i\,{}^{T_i}\boldsymbol{f}_i \tag{4} $$

where $\boldsymbol{U}_i$, $\boldsymbol{V}_i$ are homogenous transformations and $\boldsymbol{\Gamma}_i$, $\boldsymbol{\Lambda}_i$ are force transformations [9]. The sensor glove has two sensor outputs, the torques actuated by the human operator $\boldsymbol{\tau}_i$ and the finger joint angle values $\boldsymbol{\theta} \in \mathcal{R}^{10}$. From $\boldsymbol{\theta}$, $\boldsymbol{T}_i$ are calculated by forward kinematic equations and distances of the fingers from objects of the virtual world can be calculated. If fingers are in contact with the objects, the transformations $\boldsymbol{U}_i$, $\boldsymbol{V}_i$, $\boldsymbol{\Gamma}_i$ and $\boldsymbol{\Lambda}_i$ of the previous section follow immediately.

2.2 Flow from the sensor glove

The finger joint torques $\boldsymbol{\tau}_i$ of finger i are expressed as $\boldsymbol{\tau}_i = (\boldsymbol{J}_i^T)({}^{T_i}\boldsymbol{f}_i)$, where $(\boldsymbol{J}_i^T)$ is the Jacobian of finger i. The finger-tip forces ${}^{T_i}\boldsymbol{f}_i$ are

$$ {}^{T_i}\boldsymbol{f}_i = (\boldsymbol{J}_i^T)^{+}\boldsymbol{\tau}_i \,, \tag{5} $$

where $(\boldsymbol{J}_i^T)^{+}$ is the generalized inverse of the Jacobian $\boldsymbol{J}_i^T$.

Contact Model: Before transformation of the contact forces into the object coordinate frame $\boldsymbol{B}$, a specific contact model has to be chosen [8]. According to the contact model we have a number of wrenches exertable on the object which we write as unit wrenches ${}^{C_i}\boldsymbol{w}_{i,j}$ in the contact frame $\boldsymbol{C}_i$.

The contact forces ${}^{C_i}\boldsymbol{f}_i$ of (4) can be written as a linear combination of the unit wrenches ${}^{C_i}\boldsymbol{w}_{i,j}$ and a rest force ${}^{C_i}\hat{\boldsymbol{f}}_i$ as

$$ {}^{C_i}\boldsymbol{f}_i = {}^{C_i}\hat{\boldsymbol{f}}_i + \sum_{j=1}^{p_i} c_{ij}\,{}^{C_i}\boldsymbol{w}_{ij} , \tag{6} $$

where $j = 1, \ldots, k_i$, where k_i is the number of unit wrenches ${}^{C_i}\boldsymbol{w}_{i,j}$ which actually have influence on the object corresponding to the contact model. The rest force ${}^{C_i}\hat{\boldsymbol{f}}_i$ in (6) yields acceleration of the finger-tip and therewith a change of contact configuration because it is not balanced by other grasping forces or the external force. We define the contact wrench intensity vector $\boldsymbol{c}_h$ as

$$ \boldsymbol{c}_h = \left[\begin{array}{ccc} c_{11} & \ldots & c_{ij} \end{array}\right] . \tag{7} $$

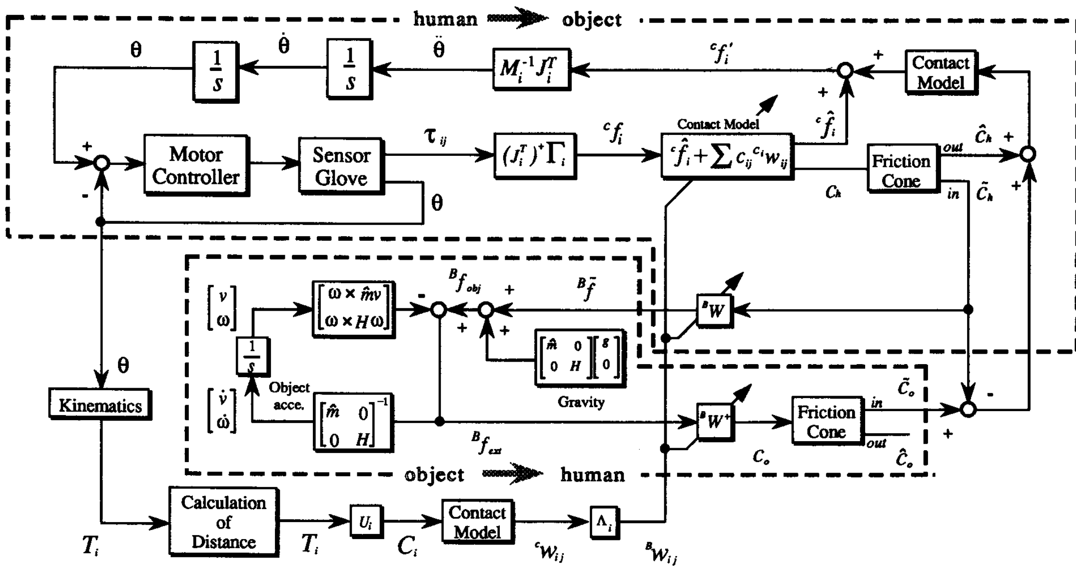


Figure 5: Dynamic Force Simulater

Friction Model: If we consider a specific friction model and therewith limit the tangential component intensities $c_{i,j}$ before transformation in the object frame and the remainder is included in ${}^{C_i}\hat{\boldsymbol{f}}_i$. Let us define $\tilde{\boldsymbol{c}}_h$ and $\hat{\boldsymbol{c}}_h$: $\tilde{\boldsymbol{c}}_h$ is acting on the object by the friction, otherwise $\hat{\boldsymbol{c}}_h$ is not acting.

Force not acting on the object: The force $\hat{\boldsymbol{c}}_h$ and ${}^{C_i}\hat{f}_i$ of (6) yield acceleration of the fingers. The contact virtual forces ${}^{C_i}\boldsymbol{f}_i'$ are

$$ {}^{C_i}\boldsymbol{f}'_i = {}^{C_i}\hat{\boldsymbol{f}}_i + {}^{C_i}\boldsymbol{W}\hat{\boldsymbol{c}}_h \tag{8} $$

where the contact wrench intensity $\hat{\boldsymbol{c}}_h$ is not acting on the object, the matrix ${}^{C_i}\boldsymbol{W}$ is given by unit wrenches ${}^{C_i}\boldsymbol{w}_{i,j}$ as

$$ {}^{C_i}\boldsymbol{W} = \left[\begin{array}{ccc} {}^{C_i}\boldsymbol{w}_{1,1} & \ldots & {}^{C_i}\boldsymbol{w}_{i,j} \end{array}\right]. \tag{9} $$

The finger joint accelerations $\ddot{\boldsymbol{\theta}}$ are calculated by the finger joint torques $\boldsymbol{\tau}_i$ of finger i as $\ddot{\boldsymbol{\theta}}_i = \boldsymbol{M}_i^{-1}(\boldsymbol{J}_i^T)({}^{C_i}\boldsymbol{f}'_i)$, where $\boldsymbol{M}_i(\boldsymbol{\theta}_i)$ is the inertia matrix. We control the position of the motors on the sensor glove by integrating $\ddot{\boldsymbol{\theta}}$ twice to get the joint angles $\boldsymbol{\theta}$.

Force acting on the object: Assuming a contact model and therewith a unit contact wrench base the matrix ${}^{B}\boldsymbol{W}$ follows, which yields complete kinematic description of the transformation between hand and object space. The unit wrenches ${}^{C_i}\boldsymbol{w}_{i,j}$ are transformed into the object coordinate frame $\boldsymbol{B}$ using (4) as ${}^{B}\boldsymbol{w}_{i,j} = \boldsymbol{A}_i\, {}^{C_i}\boldsymbol{w}_{i,j}$ and ${}^{B}\boldsymbol{W}$ of (11) follows as

$$ {}^{B}\boldsymbol{W} = \left[\begin{array}{ccc} {}^{B}\boldsymbol{w}_{1,1} & \dots & {}^{B}\boldsymbol{w}_{i,j} \end{array} \right] \tag{10} $$

where $i = 1, \dots, n$ for n fingers and $j = 1, \dots, k_i$ for k_i wrenches exerted by finger i [6][10].

The object force ${}^{B}\tilde{\boldsymbol{f}}$ becomes

$$ {}^{B}\tilde{\boldsymbol{f}} = {}^{B}\boldsymbol{W}\tilde{\boldsymbol{c}}_h \,. \tag{11} $$

2.3 Flow from the object

Let us assume a force ${}^{B}\tilde{\boldsymbol{f}}$ acting on the object in the virtual world exerted by the human hand in the sensor glove. The object force ${}^{B}\boldsymbol{f}_{obj}$ is given by ${}^{B}\tilde{\boldsymbol{f}}$ and gravitation as

$$ {}^{B}\boldsymbol{f}_{obj} = {}^{B}\tilde{\boldsymbol{f}} + \begin{bmatrix} \hat{\boldsymbol{m}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{H} \end{bmatrix} \begin{bmatrix} {}^{B}\boldsymbol{g} \\ \boldsymbol{0} \end{bmatrix} \tag{12} $$

where $\hat{\boldsymbol{m}} \in \mathcal{R}^{3\times3}$ is a diagonal matrix with the object mass in the diagonal elements, $\boldsymbol{H} \in \mathcal{R}^{3\times3}$ is the inertia matrix, ${}^{B}\boldsymbol{g}$ is the vector of gravitation.

Describing the object dynamics by the Newton-Euler equation as

$$ {}^{B}\boldsymbol{f}_{obj} = \begin{bmatrix} \hat{\boldsymbol{m}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{H} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{v}} \\ \dot{\boldsymbol{\omega}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{\omega} \times \hat{\boldsymbol{m}}\boldsymbol{v} \\ \boldsymbol{\omega} \times \boldsymbol{H}\boldsymbol{\omega} \end{bmatrix} , \tag{13} $$

where $\dot{\boldsymbol{v}}, \dot{\boldsymbol{\omega}}$ are the body accelerations, the force ${}^{B}\tilde{\boldsymbol{f}}_{ext}$ from a object to a human is given by (12) and (13) as

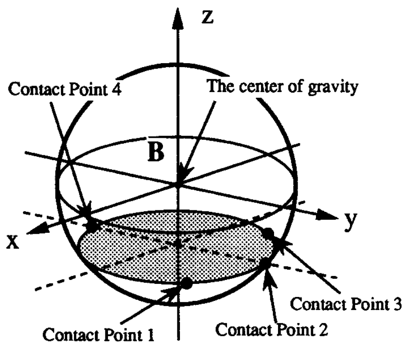
$$ {}^{B}\boldsymbol{f}_{ext} = {}^{B}\tilde{\boldsymbol{f}} + \begin{bmatrix} \hat{\boldsymbol{m}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{H} \end{bmatrix} \begin{bmatrix} {}^{B}\boldsymbol{g} \\ \boldsymbol{0} \end{bmatrix} - \begin{bmatrix} \boldsymbol{\omega} \times \hat{\boldsymbol{m}}\boldsymbol{v} \\ \boldsymbol{\omega} \times \boldsymbol{H}\boldsymbol{\omega} \end{bmatrix} = \begin{bmatrix} \hat{\boldsymbol{m}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{H} \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{v}} \\ \dot{\boldsymbol{\omega}} \end{bmatrix} . \tag{14} $$

Now let us transform ${}^{B}\boldsymbol{f}_{ext}$ from the object frame to contact frame space using

$$ \boldsymbol{c}_o = \boldsymbol{W}^{+}\, {}^{B}\boldsymbol{f}_{ext} \,, \tag{15} $$

consider friction and therewith calculate the finger contact wrench intensities $\tilde{\boldsymbol{c}}_o$ inside the friction cone, which yields acceleration of the sensor glove finger joints.

To feedback $\tilde{\boldsymbol{c}}_o$, we have to calculate the difference between $\tilde{\boldsymbol{c}}_o$ and the finger contact wrench intensities $\tilde{\boldsymbol{c}}_h$ exerted by the human hand in the sensor glove as shown Fig.3. Force feed back to the sensor glove is realized as shown in Fig.5.



Point	Contact Point		
	x	y	z
1	0.054	0.054	-0.059
2	0.000	0.076	-0.059
3	-0.054	0.054	-0.059
4	0.000	-0.076	-0.059

Figure 6: Virtual Object in Virtual World and Table of contact points

2.4 Simulation Example

Let us assume a simple example of one virtual spherical object(mass $m = 1[kg]$, radius $r = 0.1[m]$) in Fig.6. We choose a point contact model with friction. The object frame $\boldsymbol{B}$ is created as shown Fig.6 and the sphere is balanced by 4 fingers. In the first place, we do not add any kinds of forces on the object. Calculate the force ${}^{C_i}\boldsymbol{f}_i{}'$ from the object. The force acting on the object is only gravitation as

$${}^{B}\boldsymbol{f}_{ext}{}^{T} = (0.000 \;\; 0.000 \;\; -9.810 \;\; 0.000 \;\; 0.000 \;\; 0.000)$$

$\boldsymbol{c}_o$ is calculated by (15). All of $\boldsymbol{c}_o$ is acting on the object by friction, i.e. $\tilde{\boldsymbol{c}}_o = \boldsymbol{c}_o$, $\hat{\boldsymbol{c}}_o = 0$. The force ${}^{C_i}\boldsymbol{f}_i{}'$ acting on the finger-tip is given as

$$\begin{aligned}
{}^{C_1}\boldsymbol{f}_1{}' &= (-1.384 \;\; 0.693 \;\; 1.206 \;\; 0.000 \;\; 0.000 \;\; 0.000) \\
{}^{C_2}\boldsymbol{f}_2{}' &= (0.000 \;\; -1.227 \;\; 0.956 \;\; 0.000 \;\; 0.000 \;\; 0.000) \\
{}^{C_3}\boldsymbol{f}_3{}' &= (-1.384 \;\; -0.693 \;\; 1.206 \;\; 0.000 \;\; 0.000 \;\; 0.000) \\
{}^{C_4}\boldsymbol{f}_4{}' &= (0.000 \;\; 3.415 \;\; 2.662 \;\; 0.000 \;\; 0.000 \;\; 0.000) \; .
\end{aligned}$$

Using (11) and adding all ${}^{C_i}\boldsymbol{f}_i'$ yields

$${}^{B}\tilde{\boldsymbol{f}}^{T} = (0.000 \;\; 0.000 \;\; 9.810 \;\; 0.000 \;\; 0.000 \;\; 0.000) \; .$$

Therefore, the forces ${}^{C_i}\boldsymbol{f}_i$ exerted by the operator's fingers balance gravitation acting on the object. Let us now assume that ${}^{C_i}\boldsymbol{f}_i$ is 1.5 times larger than above, which yields

$${}^{B}\tilde{\boldsymbol{f}}^{T} = (0.000 \;\; 0.000 \;\; 14.715 \;\; 0.000 \;\; 0.000 \;\; 0.000) \; ,$$

and then

$${}^{B}\boldsymbol{f}_{ext}{}^{T} = (0.000 \;\; 0.000 \;\; 4.905 \;\; 0.000 \;\; 0.000 \;\; 0.000) \; .$$

The object is accelerated by half of the gravitational force. The human operator can feel the gravitation because the force ${}^{C_i}\boldsymbol{f}_i{}'$ from the object equal the first ${}^{C_i}\boldsymbol{f}_i{}'$.

3 Conclusion

In this paper we proposed the Dynamic Force Simulator (DFS) for force feedback in human-machine systems. Exact simulation of object dynamics, contact model and friction characteristics enables realistic feedback to the human operator. In this paper, we showed two influencing flows, the first one from human operator's hand in the sensor glove, and the second one from the solid state model of the DFS to the human hand.

Future work will include methods like efficient object modeling and data base construction describing the virtual world environment.

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